



**University of  
Zurich**<sup>UZH</sup>

**Zurich Open Repository and  
Archive**

University of Zurich  
University Library  
Strickhofstrasse 39  
CH-8057 Zurich  
[www.zora.uzh.ch](http://www.zora.uzh.ch)

---

Year: 2019

---

## **The status and role of the alpine cryosphere in central Asia**

Hoelzle, Martin ; Barandun, Martina ; Bolch, Tobias ; Fiddes, Joel ; Gafurov, Abror ; Muccione, Veruska ; Saks, Tomas ; Shahgedanova, Maria

DOI: <https://doi.org/10.4324/9780429436475-8>

Posted at the Zurich Open Repository and Archive, University of Zurich

ZORA URL: <https://doi.org/10.5167/uzh-181507>

Book Section

Published Version



The following work is licensed under a Creative Commons: Attribution-NonCommercial-NoDerivs 3.0 Unported (CC BY-NC-ND 3.0) License.

Originally published at:

Hoelzle, Martin; Barandun, Martina; Bolch, Tobias; Fiddes, Joel; Gafurov, Abror; Muccione, Veruska; Saks, Tomas; Shahgedanova, Maria (2019). The status and role of the alpine cryosphere in central Asia. In: Xenarios, Stefanos; Schmidt-Vogt, Dietrich; Qadir, Manzoor; Janusz-Pawletta, Barbara; Abdullaev, Iskandar. The Aral Sea basin: water for sustainable development in central Asia. Abingdon (UK): Routledge, 100-121.

DOI: <https://doi.org/10.4324/9780429436475-8>

# THE ARAL SEA BASIN

## Water for Sustainable Development in Central Asia

*Edited by*  
*Stefanos Xenarios, Dietrich Schmidt-Vogt,*  
*Manzoor Qadir, Barbara Janusz-Pawletta*  
*and Iskandar Abdullaev*

First published 2020

ISBN: 978-1-138-34888-2 (hbk)

ISBN: 978-0-429-43647-5 (ebk)

## Chapter 8

### The status and role of the alpine cryosphere in Central Asia

CC BY-NC-ND 4.0



## 8

# The status and role of the alpine cryosphere in Central Asia

*Martin Hoelzle, Martina Barandun, Tobias Bolch, Joel Fiddes,  
Abror Gafurov, Veruska Muccione, Tomas Saks and  
Maria Shahgedanova*



### Key messages

- The alpine cryosphere, including snow, glaciers and permafrost, is critical to water management in the Aral Sea Basin (ASB) and larger Central Asia (CA) under the changing climate, as it stores large amounts of water in its solid forms. Most cryospheric components in the Aral Sea Basin are close to melting point, and hence very vulnerable to a slight increase in air temperature with significant consequences to long-term water availability and to water resources variability and extremes.

- Current knowledge about different components of the cryosphere and their connection to climate in the Basin and in the entire Central Asia region varies. While it is advanced in the topics of snow and glaciers, knowledge on permafrost is rather limited.
- Observed trends in runoff point in the direction of increasing water availability in July and August at least until mid-century and increasing possibility for water storage in reservoirs and aquifers. However, eventually this will change as glaciers waste away. Future runoff may change considerably after mid-century and start to decline if not compensated by increasing precipitation.
- Cryosphere monitoring systems are the basis for sound estimates of water availability and water-related hazards associated with snow, glaciers and permafrost. They require a well-distributed observational network for all cryospheric variables. Such systems need to be re-established in the Basin after the breakup of the Soviet Union in the early 1990s. This process is slowly emerging in the region. Collaboration between local operational hydro-meteorological services and the academic sector, and with international research networks, may improve the observational capabilities in high-mountain regions of CA in general and in the ASB in particular.

## Introduction

Water resources in arid continental regions like Central Asia (CA) depend strongly on cryosphere components: snow, glaciers and permafrost (Figure 8.1). Two of the world's largest mountain systems, the Tien Shan (also: Tian Shan) and Pamir Mountains, serve as water towers for CA, of which the Aral Sea Basin (ASB) is a major part. The cryosphere components of these mountain systems store large amounts of water in a solid form and play a key role for current and future water availability and management under a changing climate. Several recent studies (Hagg *et al.* 2007; Hagg *et al.* 2013; Huss and Hock 2018; Kaser *et al.* 2010) indicate that a) in arid regions like CA, water release by snow and glaciers is fundamental to maintaining sufficient runoff during the dry summer months and b) by the end of this century the water contribution of glaciers will be drastically reduced and some catchments may completely dry out. This may pose significant challenges to water resources management, energy production, the environment, disaster risk reduction, security and public health. High-quality baseline data on cryosphere components may help develop sound climate-based scenarios of future water availability.

*Snow* is temporally and spatially the most variable component of the cryosphere. It has a strong influence on the climate system but is also strongly controlled by climate. Recent observed trends derived from remote sensing (Adnan *et al.* 2017; Immerzeel *et al.* 2009; Peters *et al.* 2015), and ground measurements (e.g., Marty 2008; Serquet *et al.* 2013) indicate a seasonally reduced duration of snow cover, as well as reduced extent of snow cover, especially at lower elevations. Such changes are important as snow has strong feedback processes, particularly over its strong albedo difference in comparison to surfaces like water, vegetation, bedrock or sediments. While glaciers release most of their melt water during the hot summer months, water from snowmelt mostly comes in spring (April, May, June). Therefore, snow storage can be seen as a temporary water reservoir accumulating snow in winter and releasing water to rivers and streams in spring and early summer. The melt water from seasonal snow cover is vital for the environment, economic development and social security of CA (e.g., (Aizen *et al.* 1995; Sorg *et al.* 2012; Unger-Shayesteh *et al.* 2013). Many ground-based stations measuring snow were abandoned after the breakup of the Soviet Union in the early 1990s, and a new observational network is only slowly evolving in the region.





Figure 8.1 Abramov glacier: one of the reference glaciers in Central Asia, where measurements were re-established in 2011 after a gap of 12 years

Source: Martin Hoelzle, August 2011

Glaciers today are the most well-known symbol of changing climate as they are at many places close to melting point and therefore highly sensitive to changes in air temperatures. Their response to warming trends is well-manifested by fast-retreating glacier tongues or even whole glaciers collapsing and decaying over very short time periods (Kääb *et al.* 2018; Paul and Mölg 2014; Zemp *et al.* 2006). These images have become icons of climate change (Haeberli 2008). CA is especially vulnerable to glacier changes, because runoff during the dry summer months is mainly dependent on the vast glacierized areas in Tien Shan and Pamir. In the coming decades, enhanced melting may lead to an increased runoff in spring and summer (Kaser *et al.* 2010) and cause glacier lake outburst floods (GLOF), debris flow and landslides, which can be very damaging to settlements and agriculture (Bolch *et al.* 2011; Erokhin *et al.* 2018; Kapitsa *et al.* 2017; Petrov *et al.* 2017; Stoffel and Huggel 2012). Towards the end of this century, runoff during the dry summer months is likely to continuously decrease due to reduced ice volumes (Hagg *et al.* 2007; Hagg *et al.* 2013; Huss and Hock 2018; Kure *et al.* 2013). Similar to *in situ* measurements of snow, long-term monitoring programs in CA and the ASB collapsed after the break-up of the Soviet Union and are currently being re-established with great national and international efforts.

*Permafrost* is defined by ground temperatures, which are continuously below 0°C over a period of at least one year. It mainly occurs in continental areas at high latitudes, but also in high mountains. Climate-induced changes in permafrost can lead to strong feedbacks with the

climate system, for example, by releasing bound methane or carbon dioxide through thawing of permafrost soils, which in turn reinforces the greenhouse effect (Koven *et al.* 2011). In addition, ice melting in permafrost soils causes land subsidence due to the loss of its volume. Furthermore, on inclined topography and with an increasing active layer,<sup>1</sup> erosion can intensify. Infrastructure can directly heat the permafrost in the ground, leading to local destabilization with associated prevention and maintenance costs. In high-mountain regions, recent increases in air temperature cause rock falls, landslides, debris flows and increased creep rates in rock glaciers (Delaloye *et al.* 2010; Sorg *et al.* 2015), and increased runoff from permafrost zones with high ice contents (Bolch and Marchenko 2009; Mateo and Daniels 2018). CA and the Tibetan Plateau host the largest permafrost area outside the polar regions (Gruber 2012). It covers around  $3.5 \times 10^6$  km<sup>2</sup>, which corresponds to about 15 per cent of the total areal extent of permafrost in the Northern Hemisphere. Permafrost research in high mountains only began in the late twentieth century, but since then considerable progress has been made in understanding mountain permafrost processes (Haeberli *et al.*, 2010).

The following sections examine each of the three cryosphere components in the ASB and larger CA in more detail.

### **Alpine snow cover**

The ASB river flow during the vegetation period in summer months is dominated by snow-melt, followed by glacier melt in late summer. Thus, high mountains of the ASB can be considered natural water towers of the region where winter precipitation is stored in the form of snow and melts during a warm period. The meltwater from seasonal snow cover is vital for the economic development and social security (e.g., Aizen *et al.* 1995; Sorg *et al.* 2012; Unger-Shayesteh *et al.* 2013). Also, through the snow-albedo feedback, changes in seasonal snow cover may affect local and regional climate and reinforce surface warming in ASB headwaters (e.g., Aizen *et al.* 2000).

Despite the importance of snow, the snow-related data (snow depth, snow cover, snow water equivalent, snow density) are limited in the ASB. Snow depth and snow water equivalent data are mainly available from the meteorological stations of national hydrometeorology services. In addition to station data, field survey and airborne snow data were collected during the Soviet era (Krenke 1998)<sup>2</sup>. Snow measurement surveys of this type were regularly carried out in CA, predominantly in Kyrgyzstan, Tajikistan and Uzbekistan, to assess snow storage and corresponding water availability during the vegetation period. Snow density and snow water equivalent were also recorded during these surveys. Unfortunately, the frequency of field and airborne snow surveys decreased dramatically after the breakup of the Soviet Union in 1991 (Unger-Shayesteh *et al.* 2013). Uzbekistan and Tajikistan continued a few airborne surveys but there were no such surveys in Kyrgyzstan (Glazirin 2007).

There are few studies of the long-term trends and shorter-term variability in snow cover. Aizen *et al.* (1997) analyzed snow data from 110 stations for the time period from 1940 to 1991 and found a decrease of mean annual snow depth of 8–14 cm at elevations below 2000 masl (meters above sea level) and of 6–19 cm at higher elevations. They also concluded that the number of days with snow cover decreased by nine days during this period. Glazirin (2006) analyzed snow cover duration at the Oigang and Tashkent stations from the 1930s and reported slight negative trends, which were, however, not statistically significant. Tsarev (2006) analyzed snow depth, precipitation and temperature data to estimate how climate change impacts on the maximum snow storage in the mountains of Central Asia based on a temperature-precipitation

approach. According to his results, scenarios of a temperature increase of 2°C and a precipitation decrease of 30 per cent would lead to about 30 per cent less snow storage in March when snow accumulation peaks. Merkushev and Tsarev (2007) introduced an empirical relationship between snow parameters and elevation that can be used to estimate snow parameters for any basin and assess impacts of climate change scenarios.

Remote sensing products have become an important source of snow data in mountainous areas of the ASB in the past three decades. Moderate-resolution imaging spectroradiometer (MODIS) and advanced very-high-resolution radiometer (AVHRR) data are among those that are widely used in the ASB to assess water availability. Yakovlev (2005) used the end-of-March AVHRR snow cover data for runoff modeling in the Pyanj Basin in Tajikistan. Gafurov et al. (2013) assessed the quality of MODIS snow cover data against manual observations from stations in the ASB and reported about 93 per cent accuracy. However, cloud cover prevents the efficient use of optical remote sensing in hydrological studies. Gafurov and Bårdossy (2009) developed a methodology for cloud removal and applied it in the Kokcha River Basin of the ASB. Zhou et al. (2013) used cloud-removed AVHRR snow cover data to understand snow characteristics in the ASB and reported that in the plain areas maximum snow coverage can reach up to 32 per cent of the total area and in the mountainous areas this value can exceed 80 per cent. Dietz et al. (2014) used combined AVHRR and MODIS snow cover data to understand the elevation-dependent snow cover characteristics and reported a snow cover duration rise of ~4 days per 100 m elevation. Gafurov et al. (2016) developed an all-in-one package MODSNOW-Tool, which includes all processing steps of raw MODIS data including cloud removal. This tool allows operational and automated monitoring of snow coverage at pre-defined river basins using the MODIS data. The MODSNOW-Tool is officially implemented in all five Central Asian countries (Kazakhstan, Kyrgyzstan, Tajikistan, Turkmenistan and Uzbekistan) and is currently used to improve seasonal river flow forecasts based on snow cover information obtained from remote areas (Apel et al. 2018; Kalashnikova and Gafurov 2017). Besides MODIS and AVHRR optical remote sensing snow cover maps, LANDSAT snow cover maps with high spatial resolution (30 m) were used to reconstruct glacier mass balance in selected glaciers in the ASB (Barandun et al. 2018; Kronenberg et al. 2016). Satellite radar systems, e.g., Sentinel-1, are being tested for their capability to detect snow water equivalent (Conde et al. 2019). Overall, snow cover maps, obtained from remote sensing, can significantly improve understanding of the hydrological processes in the ASB. Maps of mean monthly snow-covered area and snowmelt for the periods 1961–1990 and 2001–2010 for six major river basins in Asia, including the Amu Darya and the Syr Darya, are available at [http://waterdata.iwmi.org/Applications/Glacier\\_Snow\\_Asia/](http://waterdata.iwmi.org/Applications/Glacier_Snow_Asia/).

## Alpine glaciers

The Tien Shan Mountains host almost 15,000 glaciers, covering a surface area of about 12,400 km<sup>2</sup> (RGI Consortium 2017; Sorg et al. 2012), while both reported glacier coverage and glacier number in the Pamir (incl. Pamir Alay) Mountains are slightly higher according to the most recent inventory (~13,800 km<sup>2</sup>, No. ~17,000 (Mölg et al. 2018)). The mountain ranges are conventionally divided into Western/Northern Tien Shan (glacierized area: ~2,265 km<sup>2</sup>), Eastern Tien Shan (~2,210 km<sup>2</sup>), Central Tien Shan (~7,270 km<sup>2</sup>) and Jetisu (Dzhungarsky Alatau) (~520 km<sup>2</sup>), Pamir-Alay (~2,080 km<sup>2</sup>), Western Pamir (~9,470 km<sup>2</sup>) and Eastern Pamir (~2280 km<sup>2</sup>) (Aizen et al. 1995; Bolch et al. 2019; RGI Consortium 2017; Mölg et al. 2018). A significant part of this glacierized area is situated in the ASB (Figure 8.2). The median glacier

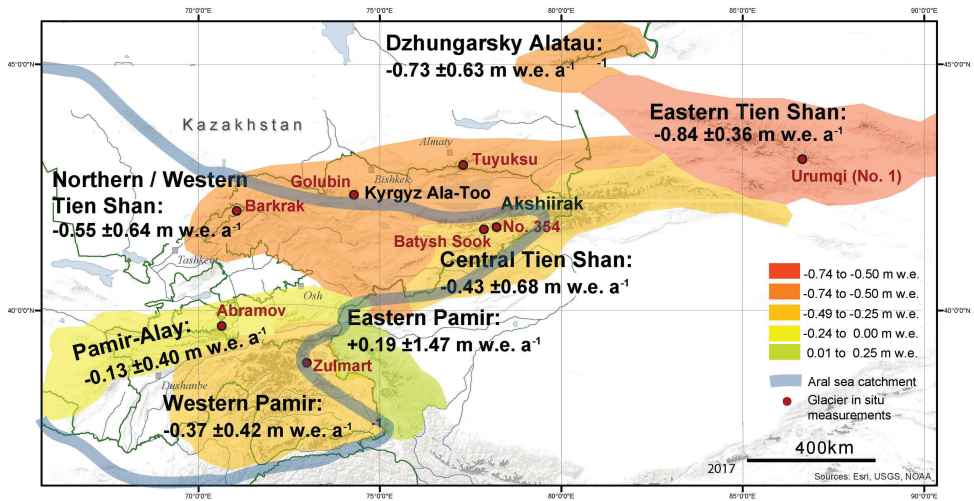


Figure 8.2 Overview map of the study region. The ASTER-derived geodetic mass change for each subregion of the Tien Shan and the Pamir derived in Barandun *et al.* (2019) are shown. The locations of all glaciers with continuous, long-term mass balance series are indicated red.

Source: Constructed by authors

elevation is highest in the Eastern Pamir (>5000 masl), slightly less than 4900 masl in the Western Pamir, approximately 4200 masl in the Central Tien Shan, and lowest in the Western and Northern Tien Shan (3700 to 3900 masl) (Mölg *et al.* 2018; Sakai *et al.* 2015). Glaciers in the west receive more precipitation during winter, whereas summer accumulation regimes become predominant towards the east (Dyurgerov *et al.* 1994; Sakai *et al.* 2015) where a combination of low temperature and summer precipitation maximum is more common (Kutuzov and Shahgedanova 2009).

## Glacier mass balance

In the 1950s, an extensive system of cryospheric monitoring in Central Asia was launched under the auspices of the USSR Committee for the International Hydrological Decade and the measurements intensified during the following years (Dyurgerov 2002; Kuzmichenok 2006; WGMS 2017). Monitoring included extensive glacier mass balance measurements on several glaciers (e.g., Central Tuyuksu, Golubin, Karabatkak, Abramov in the Soviet Union and Urumchi Glacier No. 1 in China, (WGMS 2017)). The majority of these *in situ* monitoring programs stopped in the early 1990s after the breakup of the USSR. Regular mass balance measurements continued only on Central Tuyuksu (Shahgedanova *et al.* 2018) and Urumchi Glacier No. 1 in China (WGMS 2017), neither of which, however, is in the ASB. Efforts to re-establish *in situ* glacier monitoring of the formerly monitored glaciers located in the ASB and nearby catchments have started since around 2010 through intensive international and national collaboration projects (Hoelzle *et al.* 2017). At present, mass balance is monitored on more than ten glaciers with longer measurement series. These glaciers are distributed throughout the mountain ranges of Central Asia, and Abramov, Barkrak, Batysh Sook and Glacier No. 354 are located in the ASB.



Despite this success, relative to the large number of glaciers located in this area, data remain sparse. To fill the gap in direct glaciological observations and to cover larger mountain areas, glacier volume changes were assessed on different catchment scales from local (e.g., Aizen *et al.* 2007; Bolch *et al.* 2011; Goerlich *et al.* 2017; Holzer *et al.* 2015; Li *et al.* 2017; Pieczonka and Bolch 2015) to regional studies (e.g., Brun *et al.* 2017; Gardelle *et al.* 2013; Gardner *et al.* 2013; Lin *et al.* 2017; Wang *et al.* 2017) using remote sensing. Furthermore, several mass balance time series are available from modeling studies (Farinotti *et al.* 2015; Li *et al.* 2011; Liu and Liu 2016). However, detailed region-wide mass balance time series with a high temporal resolution are still lacking.

In the Tien Shan, region-wide geodetic mass balance assessments agree on a glacier mass loss during the past two decades. Results of mass change estimates range from about  $-0.3$  m w.e.  $a^{-1}$  to  $-0.7$  m w.e.  $a^{-1}$  (Brun *et al.*, 2017; Farinotti *et al.*, 2015; Gardner *et al.*, 2013). Accelerated mass loss since the 1970s was reported for most regions (e.g., Farinotti *et al.*, 2015; Pieczonka *et al.* 2013; Sorg *et al.*, 2012). No significant acceleration of glacier mass loss could be identified since the onset of the century through snowline-constrained mass balance modeling (Barandun 2019). However, an increase in inter-annual variability was observed, pointing toward a change in the mass balance regime from a more continental to a more maritime setting, as described by Dyurgerov and Dwyer (2001). The highest geodetic mass loss was observed in the Eastern Tien Shan (not in the ASB). The lowest rates of mass loss were found in the Central Tien Shan (Figure 8.2). Comparison of the different geodetic assessments showed a good agreement for the Inner and Central Tien Shan (Brun *et al.* 2017; Farinotti *et al.* 2015; Gardner *et al.* 2013) and for the Northern/Western Tien Shan (Bolch 2015; Brun *et al.* 2017; Gardner *et al.* 2013). For the two aforementioned regions, an ASTER-derived average mass loss of approximately  $-0.5$  m w.e.  $a^{-1}$  and  $-0.4$  m w.e.  $a^{-1}$ , respectively, was calculated from 2004 to 2012.

Published mass change assessments for the Pamir show quite large divergence and range from a close to balanced budget ( $+0.14$  to  $-0.13$  m w.e.  $a^{-1}$ ; Brun *et al.* 2017; Gardelle *et al.* 2013; Gardner *et al.* 2013; Kääb *et al.* 2015) to strongly negative mass balances ( $-0.48$  to  $-0.52$  m w.e.  $a^{-1}$ ; Kääb *et al.* 2015; Pohl *et al.* 2017). There are still discrepancies between the assessments, leading to debates over the ambiguous mass balance regime and its change. Important methodological differences, input data quality, inconsistent study periods and spatial divisions can explain the differences to some extent. A compilation and reassessment of the different published geodetic estimates revealed, on average, a mass loss of  $0.26$  m w.e.  $a^{-1}$  for Western Pamir and balanced budgets for the Eastern Pamir ( $-0.02$  m w.e.  $a^{-1}$ ) for the period after 2000 (Bolch *et al.* 2019). This is in line with recent geodetic estimates by Barandun (2019), who reports  $-0.37 \pm 0.42$  m w.e. for the Western Pamir and  $+0.19 \pm 1.47$  m w.e. for the Eastern Pamir.

The reanalyzed historical glaciological measurements, reconstructed mass balance data and re-initiated *in situ* measurements provide a comprehensive and complete mass balance time series for Abramov, Golubin, Batysh Sook and Glacier No. 354 (Barandun *et al.* 2018; Barandun *et al.* 2015; Kenzhebaev *et al.* 2017; Kronenberg *et al.* 2016). Modern direct measurements revealed mass losses ranging from  $-0.25$  to  $-0.51$  m w.e.  $a^{-1}$  (2011–2016) and reconstructed mass balances confirmed the negative signal for the last decades for these glaciers ( $-0.30$  to  $-0.43$  m w.e.  $a^{-1}$  from 2000 to 2014; Barandun *et al.* 2018; Barandun *et al.* 2015; Hoelzle *et al.* 2017; Kenzhebaev *et al.* 2017; Kronenberg *et al.* 2016). The first mass balance calculations reported moderate mass loss of  $-0.10$  to  $-0.25$  m w.e.  $a^{-1}$  for Barkrak Middle Glacier in Uzbekistan for 2017–2018 (unpublished results). For Abramov, geodetic

mass change of  $-0.36 \pm 0.07$  m w.e.  $a^{-1}$  derived from aerial photographs and high-resolution optical satellite data for 1975 to 2015 also agreed with reanalyzed and reconstructed time series (Denzinger 2018). Unfortunately, meaningful comparison between the different studies was not always straightforward due to a very limited number of studies assessing the mass change of individual glaciers in the region and due to differences in study periods. New developments try to implement tools allowing for an optimal reconstruction of annual mass balance time series of a large amount of unmeasured and remote glaciers on mountain range scales based on a sophisticated combination of *in situ* and remote measurements coupled with different models. The resulting mass balance time series permit the determination of annual mass balance variability for a large number of glaciers in the Tien Shan and Pamir, with minimal cost and labor effort (Barandun 2019).

### **Glacier area changes**

Several studies employed remote sensing techniques to map glacier area fluctuations (e.g., Bolch 2007; Khromova *et al.* 2003; Khromova *et al.* 2006; Narama *et al.* 2010; Ozmonov *et al.* 2013; Shangguan *et al.* 2006). Glacier retreat and reduction in glacier area are observed throughout the Tien Shan but rates of retreat vary (Sorg *et al.* 2012; Unger-Shayesteh *et al.* 2013). In the Pamir, glacier change follows a more heterogeneous pattern (Knoche *et al.* 2017). Generally, the highest loss of glacierized area is observed in the outer regions and at lower elevations, while in the inner regions, in the inter-mountain basins and in the higher-elevation regions of the Pamir and Tien Shan the observed glacier shrinkage is slower (Aizen *et al.* 2014; Narama *et al.* 2010; Sorg *et al.* 2012; Unger-Shayesteh *et al.* 2013). A comparison of glacier area change in the Pskem (the western part of the ASB, with a mean elevation of the glacierized area of 3000 masl), At Bashy and the southeastern Ferghana ranges (inner ranges in the southeastern part of the ASB with a mean elevation of 3500 masl) show that in the Pskem Basin glaciers lost 19 per cent and 5 per cent in the 1970–2000 and 2000–2007 periods, while in the At Bashy and Ferghana ranges they lost 12 per cent and 4 per cent, and 9 per cent and 0 per cent in the same periods, respectively (Narama *et al.* 2010). For the Naryn Basin, Kriegel *et al.* (2013) reported a glacier area reduction of 23 per cent for the 1970s–mid-2000s period. In most basins (e.g., Pskem, At Bashy, Naryn) an acceleration in glacier shrinkage is reported in the twenty-first century, particularly in the catchments where small glaciers (which also tend to be located at lower elevations) prevail.

### **Climate considerations**

The sensitivity of glaciers to increasing summer temperatures is assumed to be responsible for the long-term retreat (Glazirin *et al.* 2002); however, changes in precipitation should not be disregarded. In particular, a well-documented step reduction in precipitation observed in Central Asia in the 1970s, driven by changes in atmospheric circulation, led to a decrease in annual mass balance due to a reduction in accumulation (Cao 1998; Shahgedanova *et al.* 2018). More recent changes in precipitation are non-uniform across the region. Many studies report no statistically significant long-term trends in annual or seasonal precipitation while stressing strong inter-annual variability (Chevallier *et al.* 2014; Finaev 2006; Kriegel *et al.* 2013; Narama *et al.* 2010; Shahgedanova *et al.* 2018). An increasing number of positive-degree days in the high-elevation regions suggests a growing frequency of days with liquid precipitation (Kriegel *et al.*, 2013) which results in lower accumulation and further enhancement of glacier



melt through suppressing surface albedo. Some of the earlier studies, considering changes in precipitation in the 1970s–2000s, reported increasing trends (Unger-Shayesteh *et al.* 2013). Considering the negative mass budget of the glaciers in the ASB, these did not compensate for the increase in air temperature (Khromova *et al.* 2006).

## Alpine permafrost

### *Tien Shan and Pamir permafrost distribution*

Continuous permafrost exists above 3600 masl in the central-northern Tien Shan Mountains. The discontinuous zone extends from 3200 to 3600 masl, while the sporadic zone is present from 2700 to 3200 masl (Figure 8.3). Within these zones, permafrost spread may be strongly influenced by local topography and other ground conditions.

Since the end of the Little Ice Age, permafrost in the Tien Shan Mountains experienced a continuous warming until present (Marchenko *et al.* 2007). The first systematic permafrost temperature measurements in the Northern Tien Shan began in 1973 (Gorbunov and Nemov 1978). Initial geothermal observations (1974–1977) in boreholes in the Northern Tien Shan showed that permafrost temperatures within loose deposits and bedrock at an altitude of 3300

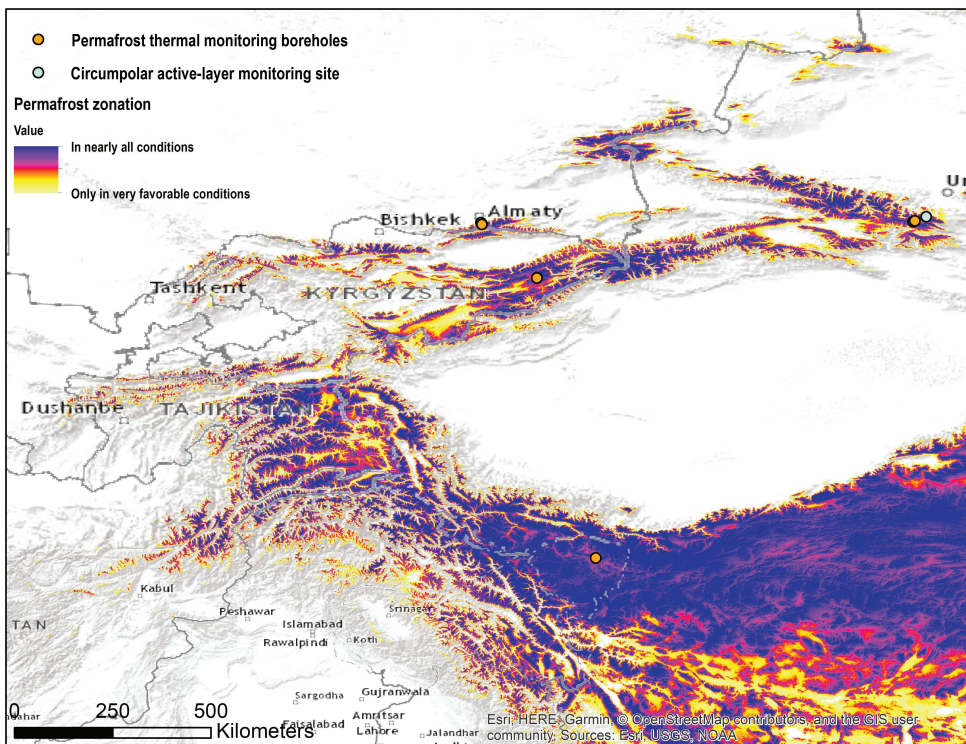


Figure 8.3 World Terrain Base map showing permafrost zonation, locations of boreholes and active-layer monitoring sites in Central Asia (after Gruber 2012)

Source: Constructed by authors

masl vary from  $-0.3^{\circ}\text{C}$  to  $-0.8^{\circ}\text{C}$  (Gorbunov and Nemov 1978). Thickness of permafrost in this area varied from 15 to 90 m and the maximum active-layer thickness reached 3.5–4.0 m (Gorbunov and Nemov 1978). Permafrost investigations in the Inner Tien Shan were performed between 1985 and 1992. The results of these investigations included permafrost temperature records, active-layer thickness measurements, descriptions of the cryogenic structures of frozen ground maps, and charts of the distribution of permafrost, ground ice, and periglacial landforms. Ground temperature measurements were carried out in 20 boreholes in the Akshiirak massif ( $42^{\circ}\text{N}$ , between 4000 and 4200 masl), and in more than 25 boreholes in the Kumtor Valley (between 3560 and 3790 masl). In the Akshiirak Mountain Range, at elevations of 4100–4200 masl, the lowest measured ground temperature was  $-5^{\circ}\text{C}$  in the bedrock (Paleozoic schist) and  $-6.7^{\circ}\text{C}$  in the ice-rich Late Pleistocene moraines. The corresponding thickness of permafrost was 350–370 m and 250–270 m, respectively (Gorbunov *et al.* 1996). Thickness of the active layer on the western slope of the Akshiirak massif decreased from 2.5–3.5 to 0.5–0.7 m within 3200–4000 masl. In the southwestern part of the Tien Shan (Chatyr-Kol and Aksai depressions,  $40^{\circ}30'\text{N}$ ), at an elevation of 3500–3600 masl, the thickness of permafrost in loose deposits was 60–90 m and its temperatures were between  $-1.2$  and  $-1.6^{\circ}\text{C}$ . The geothermal gradient in the Tien Shan changes from  $0.01^{\circ}\text{C m}^{-1}$  at the mountain ridges and up to  $0.02$ – $0.03^{\circ}\text{C m}^{-1}$  at the bottom of the valleys and within the mountain depressions (Schwarzman 1985).

It is important to note that the 3D topography of the mountains strongly controls the heat flow direction. In steep mountainous topography the heat flow in the area of mountain peaks in the Northern Hemisphere is in general not vertical but more horizontal from the warm southern side to the cold northern side (Magnin *et al.* 2015; Magnin *et al.* 2017; Noetzli and Gruber 2009; Noetzli *et al.* 2007). This is particularly important when interpreting temperature measurements in deep boreholes as the temperature profiles are heavily impacted by the topography (Gruber *et al.* 2004). Relict Pleistocene permafrost was found in the Aksai depression ( $40^{\circ}55'\text{N}$ ,  $76^{\circ}25'\text{E}$ ) at an elevation of 3160 masl. A 400-meter-deep borehole revealed a two-layered permafrost structure with a lower layer of frozen clay at a depth between 214 and 252 m (Aubekerov and Gorbunov 1999). The thickness of the modern upper layer of permafrost is 90–110 m. This is the one single observation of relic permafrost in the Tien Shan Mountains.

Permafrost temperature observations during 1974–1977 and 1990–2009 indicate that the ground has warmed in the Kazakh part of Tien Shan Mountains over the past 35 years. The increase from 1974 to 2009 varies from  $0.38^{\circ}\text{C}$  to  $0.68^{\circ}\text{C}$  at depths of 14–25 m. Based on interpolation of borehole temperature data, the active layer increased in thickness from 3.2 to 3.4 m in the 1970s to a maximum of 5.2 m in 1992 and to 5.0 m in 2001 and 2004. The average active-layer thickness for all measured sites increased by 23 per cent in comparison to the early 1970s (Marchenko *et al.* 2007).

In the Pamir, knowledge on permafrost distribution, properties and impacts is limited. Müllebnner (2010), using datasets provided by the Tajik hydro-meteorological service, derived an elevation of 3300 masl for the  $0^{\circ}\text{C}$  isotherm. This elevation was interpreted as the approximate lower boundary (without considering surface offsets) for permafrost in Tajikistan. That constitutes approximately 44.3 per cent of the total area of Tajikistan as potential permafrost area and up to 84.1 per cent of the eastern Pamir (Gruber and Mergili 2013; Mergili *et al.* 2012).

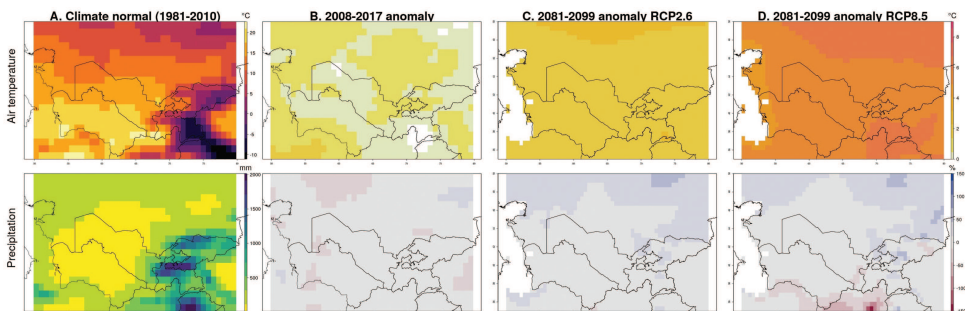
The few thickness measurements in the Karakul lake area suggest relatively thin and unevenly distributed permafrost. Reported thicknesses range from 21–22 m near the eastern coast of Lake Karakul (elevation approximately 3900 masl), while approximately 1 km to the east

of this site a permafrost thickness of 120–140 m has been reported from drill sites (Gorbunov *et al.* 1996). Further south, in the Rangul depression, the permafrost thickness is just 15 m at an altitude of 3800 masl, while at the elevation range from 4050–4150 masl it varies from 25 to 110 m (Gorbunov 1978).

### ***Permafrost and changing climate***

Overall, very little progress has been made so far in quantifying changes of permafrost under future climate in CA. Mean annual air temperature is the primary climate control on permafrost extent, further modified by surface–atmosphere interactions (mainly snow cover thickness and duration) controlled by topography and surface cover. Clear increasing trends in mean temperature have been observed throughout the CA region (Figure 8.4) with the possible exception of the central Pamir region, which may be affected by the so-called *Karakoram anomaly* (Forsythe *et al.* 2017). These trends are expected to continue in the future, as projected by all scenarios from the most recent Coupled Model Intercomparison Project– Phase 5 (CMIP5) and hence widespread permafrost degradation in CA may be expected.

As mountain permafrost slopes warm, they tend to destabilize, primarily through reduced mechanical strength, potentially leading to various types of mass movements such as debris flows, rock avalanches, or, in the case of ice-cored moraine dams, glacial lake outburst floods (GLOFS). Mass movements are complex phenomena and while climate-induced permafrost degradation (observed at GTNP<sup>3</sup> sites in Tien Shan, e.g., Marchenko *et al.* 2007) can be a key driver of such events, it is not straightforward to disentangle the climate signal from normal erosional processes in mountain regions. However, there is increasing evidence that increased incidence of thermally induced slope instabilities should be expected as high-mountain regions warm. Due to the high potential energy inherent in steep environments and the possibility of compound events that entrain moisture sources (glacier ice, snow or water), the consequences of mass movements can be far-reaching and affect communities many kilometers downstream.



**Figure 8.4** Observed and projected climate change in Central Asia as reported by ERA-Interim reanalysis for climate normals: (A) and current anomaly (B) and GCM multimodal means (Hempel *et al.* 2013) for RCP2.6 (C) and RCP8.5 (D) (projected changes 2081–2099). Cooling of up to 1°C is shown in white in panel (B) and corresponds to the so-called ‘Karakoram anomaly’. Note all temperature scales are in °C, precipitation normal is in mm whereas precipitation anomalies are in % change

Source: Constructed by authors

### ***Permafrost as a potential water resource***

Central Asia is a relatively arid region where permafrost ice could be a significant contributor to the hydrological cycle as compared to more humid regions, e.g., the European Alps, particularly in the latter half of the twenty-first century, when glacial contributions are projected to be sharply reduced (Huss and Hock 2018). According to Gorbunov *et al.* (1996) the total volume of ground ice in the Northern Tien Shan is 56 km<sup>3</sup>, which equals 62 per cent of the surface ice volume for the same territory, underscoring its potential value as a water resource (Bolch and Marchenko 2009). Furthermore, it has been estimated that the ratio of rock glacier to surface ice in CA is several times higher than in the European Alps. Permafrost responds more slowly to climate due to the insulating effect of the overlying active layer together with ventilation effects, mainly caused by coarse blocky surface material. Permafrost-based water resources are therefore likely to be available long after surface ice is heavily depleted.

### ***Improving permafrost monitoring***

While much research activity has focused on permafrost of the Northern Tien Shan (Bolch and Gorbunov 2014; Bolch and Marchenko 2009; Gorbunov and Titkov 1992; Marchenko *et al.* 2007; Sorg *et al.* 2015), to date there is a paucity of information throughout the Pamir region. The region has a total of two permafrost boreholes listed in the GTNP database.<sup>4</sup> Continuous *in situ* measurements and monitoring in remote mountain areas of CA are challenging due to difficult access, complex topography, financial and logistic constraints, political instability, as well as lack of appropriate infrastructure (Hoelzle *et al.* 2017; Unger-Shayesteh *et al.* 2013). There are very few datasets above 3000 masl and virtually none above 5000 masl. If meteorological stations are present at all, they are usually located at lower elevations where most of the population lives. Remote sensing data as well as model-assimilated observations (from reanalysis data) are used to fill the observational gap. However, the relatively short time series and coarse resolution do not allow for robust assessments of changes in mountain areas with complex topography (Prein *et al.* 2015). This makes the case for denser observational networks in remote mountain areas ever more urgent.

### **Runoff trends and water-related hazards in headwater catchments**

While a decline in the streamflow of the Amu Darya and Syr Darya are well documented (Micklin 2007), changes in discharge of their tributaries, particularly in the headwater catchments, have received less attention (Chevallier *et al.* 2014). Existing studies suggest that long-term (50–60 years) trends in streamflow in the unmodified headwater catchments (where cryosphere components are present) annually or during the melt season are either insignificant or inconsistent. Contrasting runoff trends were reported by Khan and Holko (2009), who analyzed the reconstructed natural flow time series for the gauges Chinaz (close to the border between Uzbekistan and Kazakhstan, taken as representative for the upper Syr Darya Basin) and Kerki (near the border between Afghanistan and Turkmenistan, representing the upper Amu Darya Basin). Kriegel *et al.* (2013) examined the long-term time series of monthly streamflow in the headwaters of the Big Naryn and the Small Naryn, concluding that August is a month in which glacier melt is expected to make the most prominent contribution to discharge. According to these observations, streamflow declined by 20 per cent and increased by 21 per cent in the Small Naryn and Big Naryn respectively, but there were no significant trends in summer streamflow of either river between 1960 and 2007.

Studies analyzing trends in streamflow over shorter time periods show an increase in streamflow; for example, Finaev (2006) reported positive trends at several gauges in the Pamir for the 1990–2005 period but acknowledges that poor data quality may have affected the results. Although few, the existing analyses of discharge in the headwater catchments of the ASB and some neighboring basins (Shahgedanova *et al.* 2018; Duethmann *et al.* 2015; Krysanova *et al.* 2015; Kundzewicz *et al.* 2015) show that, to date, summer streamflow has not declined. However, the relative contributions of glacier, snow and permafrost may need more insights.

The current observed trends in streamflow and runoff point in the direction of increased water availability in July and August at least until mid-century and increased possibility for water storage in reservoirs and aquifers. However, eventually this will change as glaciers waste away; runoff patterns may change considerably after mid-century (Sorg *et al.* 2014). In a global effort to model runoff changes of more than 50 glacierized basins worldwide, Huss and Hock (2018) found that annual glacier runoff from about half of the basins will continue to increase until *peak water* is reached, and will start to decline afterwards (Figure 8.5).

Peak water will occur later in areas with a higher glacierized fraction and a higher altitudinal distribution of the ice masses. Seasonal runoff is expected to increase in early summer but decrease in late summer. Depending on the climate scenarios employed, peak water will occur in  $2030 \pm 2$  (RCP2.6, mitigation scenario), and  $2044 \pm 15$  (RCP8.5, business-as-usual scenario) in the ASB. Correspondingly, their model predicts an annual runoff increase for the ASB until peak water of 37 per cent (RCP2.6) and 53 per cent (RCP8.5). The increasing rate of evapotranspiration in a warmer climate combined with reduced water flow once peak water has been reached might further intensify challenges for water availability and management (Cretaux *et al.* 2013). However, studies focusing on predicting peak water on a smaller scale (individual catchments) are still lacking for the region and they are necessary in order to better assess the vulnerability of the local populations in the coming decades.

Changes in water resources are to be understood also in terms of changes in the frequency and distribution of water-related hazards, such as river floods, glacier lake outburst floods (GLOFs) and rain-on-snow events (rapid melting of snow combined with intense precipitation). Recent studies have reported that the number and extent of glacier lakes is increasing around the world as a consequence of increased temperatures in high-mountain areas (Carrivick and Tweed 2013; Tweed and Carrivick 2015; Wang and Zhang 2013) and that this trend will continue into the future (Kapitsa *et al.* 2017). The formation of ice- and moraine-dammed lakes from increased glacier melt has the potential to generate glacier lake outburst floods (GLOFs) hazards. The Dasht event in 2002 in the Shakh dara Valley (southwestern Tajik Pamir) is a stark reminder of the destructive power of such events. During the event 250,000 m<sup>3</sup> of water was released. The flow of water and entrained debris travelled about 10 km downstream to Dasht village. Large sections of the village were destroyed and the event claimed the life of more than 20 people (Komatsu and Watanabe 2014). Another more recent GLOF event in the Teztor Valley (Ala-Archa River catchment in the Tien Shan) in northern Kyrgyzstan in 2012 entrained a debris flow that caused minor disruption to the capital Bishkek (Erokhin *et al.* 2018). The event was preceded by intense precipitation and rapid rise in temperature, which are believed to have been the cause (Erokhin *et al.* 2018).

More than 1500 lakes extending across Tajikistan, Kyrgyzstan and Afghanistan have been identified through satellite remote sensing (Mergili *et al.* 2013). Kyrgyzstan alone counts about 2000 glacial lakes in its territory, of which 20 per cent are considered at potential risk of outburst due to unstable dams and frequent overflows (Janský *et al.* 2008). A new glacier lake inventory for the Uzbekistan territory (Petrov *et al.* 2017) identified 242 in the four Uzbekistan



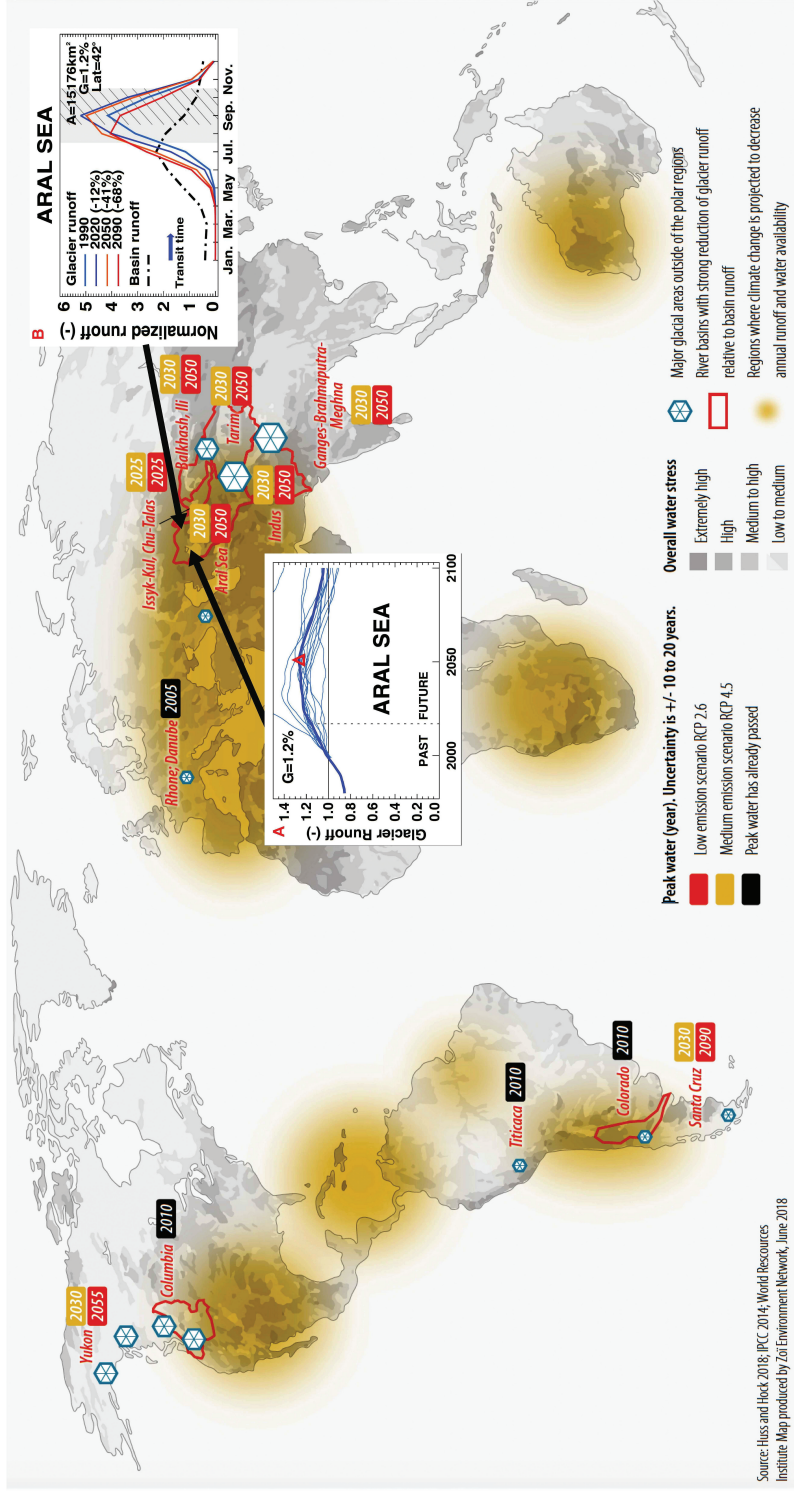


Figure 8.5 Simulated timing of peak water for individual macro-scale glacierized drainage basins (Huss and Hock 2018). Results refer to runoff from the initially glacierized area and are based on the multi-model mean of 14 GCMs and the RCP4.5 emission scenario. Inset (A) shows calculated annual glacier runoff normalized by average runoff in 1990–2010 for the ASB. The red triangle depicts peak water and the thin lines show results for individual GCMs. Inset (B) shows monthly mean basin runoff and calculated mean glacier runoff (shifted by water transit time) for four 20-year periods (1980–2000, 2010–2030, 2040–2060, 2080–2100). All series are normalized to model initialization (around 1990). The modeled change in glacier area (A), glacierization (G) and geographic latitude (Lat.) of the basin's center are given. Shaded areas on the Inset indicate a monthly share of glacier runoff relative to total basin runoff of >30 per cent and hatched areas denote months. Basin-specific transit times are indicated with the blue arrow

Source: Constructed by authors



mountain regions, with more than half (131) located in the Tashkent region. Forty per cent of these (97 lakes) were classified to have a high outburst potential.

The increase in number and extent of glacier lakes does not appear to be accompanied by an increase in glacial floods (Harrison *et al.* 2018). Conversely, some studies have suggested a global decline in glacier floods since the 1990s, possibly associated on the one side with delayed response of glacier flood activities with glacier retreat (Harrison *et al.* 2018), and on the other side with the capacity of successive floods to give rise to river channels, which are better suited to accommodate subsequent flood events (Carrivick and Tweed 2016).

Global and regional climate models point in the direction of future increase in the intensity and frequency of extreme precipitation (Seneviratne *et al.* 2016). At high altitude and/or latitude, extreme precipitation and higher temperature might exacerbate the frequency of rain-on-snow flood events, which are responsible for the most damaging floods in mountain areas (Würzer *et al.* 2016). Furthermore, precipitation extremes combined with reduced snow and ice might be responsible for increased sediment transport and subsequent deterioration of water quality, infiltration in hydropower reservoirs and damage to infrastructure and agriculture (Huss *et al.* 2017). A wide knowledge gap exists on the future evolution of extreme events and their impacts on people, infrastructure and livelihoods in Central Asia (Unger-Shayesteh *et al.* 2013; Xenarios *et al.* 2019).

## Conclusions

With its two large mountain ranges, Tien Shan and Pamir, Central Asia contains a large part of the worldwide alpine cryosphere, which has a fundamental function as a water storage reservoir with very different temporal scales, as described in this chapter. The state of current knowledge about the different cryospheric components, their processes, and their connection to climate in the Central Asian mountains and in the ASB catchment in particular varies. In the areas of snow and glacier research, knowledge in CA is quite advanced, whereas in permafrost research it is still marginal. Considerable work has been undertaken since the 1990s to address existing research gaps. One basic prerequisite for sound future estimates of cryospheric changes in the Central Asian mountains is the re-establishment of high-quality monitoring sites and capacity building, i.e., the education of young local scientists being able to continue the existing as well as new monitoring programs and to independently build up local research capacities. Currently such capacities and innovations are strongly supported through international projects such as the Central Asia Water project (CaWA<sup>5</sup>), an international consortium of German and Central Asian institutions, the Capacity Building and Twinning Climate Observing System and Cryospheric Climate Services for Improved Adaptation of the Swiss Agency for Development and Cooperation (CATCOS<sup>6</sup> and CICADA<sup>7</sup>), and the Central Asia Hydrometeorology Modernization Project (CAHMP<sup>8</sup>) of the World Bank, and many projects supported by the UK Newton Fund and Global Challenges Research Fund.

The modern alpine cryospheric network of Switzerland can serve as a role model for the mountainous countries in Central Asia. Swiss cryospheric monitoring networks (such as PERMOS, GLAMOS, or the snow monitoring network) are mainly funded by the Swiss government and are implemented primarily by researchers of different universities and research institutions. This is a reliable model that has extended operational monitoring capabilities beyond regions traditionally serviced by standard operational centers. A focus on collaboration between traditional operational hydro-meteorological services with academic sectors and the international networks they leverage could also be a model for improving the observing capabilities in high-mountain regions of CA in general, and the ASB in particular.

## Notes

- 1 Active layer corresponds to the layer of ground that is subject to annual thawing and freezing in areas underlain by permafrost.
- 2 Data from National Snow and Ice Data Center, Central Asian snow cover from hydrometeorological surveys, 1932–1990, <https://nsidc.org/data/g01171>.
- 3 Global Terrestrial Network for Permafrost mandated by Global Climate Observing System/WMO.
- 4 <http://gtnpdatabase.org/boreholes>.
- 5 <http://cawater-info.net/>.
- 6 [www.meteoschweiz.admin.ch/home/forschung-und-zusammenarbeit/projekte.subpage.html/de/data/projects/2011/catcos.html](http://www.meteoschweiz.admin.ch/home/forschung-und-zusammenarbeit/projekte.subpage.html/de/data/projects/2011/catcos.html).
- 7 [www.unifr.ch/geoscience/geographie/en/research/integrated-themes/international-cooperation-capacity-building](http://www.unifr.ch/geoscience/geographie/en/research/integrated-themes/international-cooperation-capacity-building).
- 8 <http://projects.worldbank.org/P120788/central-asia-hydrometeorology-modernization-project?lang=en>.

## References

- Adnan, M., Nabi, G., Poomee, M. S., and Ashraf, A., 2017, Snowmelt runoff prediction under changing climate in the Himalayan cryosphere: the case of the Gilgit River Basin: *Geoscience Frontiers*, v. 8, pp. 941–949.
- Aizen, E. M., Aizen, V. B., and Melack, J. M., 2000, Heat exchange during snow ablation in plains and mountains of Eurasia: *Journal of Geophysical Research*, v. 105, pp. 13–22.
- Aizen, V. B., Aizen, E. M., 2014, The Central Asia climate and cryosphere/water resources changes. In CAIAG (ed.), Materials of the International Conference ‘Remote- and Ground-based Earth Observations in Central Asia’. CAIAG, Bishkek, Kyrgyzstan, 8–9 September 2014
- Aizen, V. B., Aizen, E. M., and Kuzmichenok, V., 2007, Glaciers and hydrological changes in the Tien Shan: simulation and prediction: *Environmental Research Letters*, v. 2, no. 045019, doi:10.1088/1748-9326/1082/1084/045019.
- Aizen, V. B., Aizen, E. M., and Melack, J. M., 1995, Climate, snow cover, glaciers, and runoff in the Tien Shan, Central Asia: *Water Resources*, v. 31, no. 6, pp. 1113–1129.
- Aizen, V. B., Aizen, E. M., Melack, J. M., and Dozier, J., 1997, Climatic and hydrologic changes in the Tien Shan, Central Asia: *Journal of Climate*, v. 10, pp. 1393–1404.
- Apel, H., Abdykerimova, Z., Agalhanova, M., Baimaganbetov, A., Gavrilenko, N., Gerlitz, L., Kalashnikova, O., Unger-Shayesteh, K., Vorogushyn, S., and Gafurov, A., 2018, Statistical forecast of seasonal discharge in Central Asia using observational records: development of a generic linear modelling tool for operational water resource management: *Hydrology and Earth System Science*, v. 22, pp. 2225–2254.
- Aubekerov, B. and Gorbunov, A., 1999, Quaternary permafrost and mountain glaciation in Kazakhstan: *Permafrost and Periglacial Processes*, v. 10, pp. 65–80.
- Barandun, M., 2019, A novel approach to estimate glacier mass balance in the Tien Shan and Pamir based on transient snowline observations [Ph.D]. University of Fribourg, Switzerland.
- Barandun, M., Huss, M., Berthier, E., Kääb, A., Azisov, E., Bolch, T., Usulbajev, R., and Hoelzle, M., 2018, Multi-decadal mass balance series of three Kyrgyz glaciers inferred from transient snowline observations: *The Cryosphere*, v. 12, pp. 1899–1919.
- Barandun, M., Huss, M., Sold, L., Farinotti, D., Azisov, E., Salzmann, N., Usulbaliev, R., Merkushev, A., and Hoelzle, M., 2015, Re-analysis of seasonal mass balance at Abramov glacier 1968–2014: *Journal of Glaciology*, v. 61, no. 230, pp. 1103–1117.
- Bolch, T., 2004, *Using ASTER and SRTM DEMs for Studying Glaciers and Rockglaciers in Northern Tien Shan: Theoretical and Applied Problems of Geography on a Boundary of Centuries* [Teoreticheskiye i Prikladnyye Problemy geografii na Rubezhe Stoletij], Kazakh National University, Almaty, Kazakhstan, pp. 254–258
- Bolch, T., 2007, Climate change and glacier retreat in northern Tien Shan (Kazakhstan/Kyrgyzstan) using remote sensing data: *Global and Planetary Change*, v. 56, pp. 1–12.
- Bolch, T., 2015, Glacier area and mass changes since 1964 in the Ala Archa Valley, Kyrgyz Ala-Too, Northern Tien Shan: *Led i Sneg (Ice and Snow)*, v. 55, no. 1, pp. 28–39.
- Bolch, T. and Marchenko, S., 2009, Significance of glaciers, rockglaciers and ice-rich permafrost in the Northern Tien Shan as water towers under climate change conditions. In Braun, L. N., Hagg, W., Severskiy, I. V., and Young, G. (eds), *Proceedings Assessment of Snow, Glacier and Water Resources in Asia*,

- Almaty, Kazakhstan, 2006, Volume 8. UNESCO-IHP and German IHP/HWRP National Committee, Koblenz, Germany, pp. 132–144.
- Bolch, T. and Gorbunov, A.P. 2014, Characteristics and origin of the rock glaciers in northern Tien Shan (Kazakhstan/Kyrgyzstan): *Permafrost and Periglacial Processes*, v. 25, no. 4, pp. 320–332.
- Bolch, T., Peters, J., Yegorov, A., Pradhan, B., Buchroithner, M., and Blagoveshchensky, V., 2011, Identification of potentially dangerous glacial lakes in the northern Tien Shan: *Natural Hazards*, v. 59, no. 3, pp. 1691–1714.
- Bolch, T., Shea, J. M., Shiyin, L., Azam, M. F., Gao, Y., Gruber, S., Immerzeel, W. W., Kulkarni, A., Li, H., Tahir, A. A., Zhang, G., and Zhang, Y., 2019, Status and change of the cryosphere in the extended Hindu Kush Himalaya region. In Wester, P., Mishra, A., Mukherji, A., and Shrestha, A. B. (eds), *The Hindu Kush Himalaya Assessment*. Springer, Cham, Switzerland, pp. 209–255.
- Brun, F., Berthier, E., Wagnon, P., Kääb, A., and Treichler, D., 2017, A spatially resolved estimate of high mountain asia glacier mass balances, 2000–2016: *Nature Geoscience*, v. 10, no. 9, pp. 668–673.
- Cao, M. S., 1998, Detection of abrupt changes in glacier mass balance in the Tien Shan Mountains: *Journal of Glaciology*, v. 44, no. 147, pp. 352–358.
- Carrivick, J. L. and Tweed, F. S., 2013, Proglacial lakes: character, behaviour and geological importance: *Quaternary Science Reviews*, v. 78, pp. 34–52.
- Carrivick, J. L., and Tweed, F. S., 2016, A global assessment of the societal impacts of glacier outburst floods: *Global and Planetary Change*, v. 144, p. 1–16.
- Chen, Y., Li, W., Deng, H., Fang, G., and Li, Z., 2016, Changes in Central Asia’s water tower: past, present and future: *Scientific Reports*, v. 6, pp. 35458.
- Chevallier, P., Pouyaud, B., Mojaisky, M., Bolgov, M., Olsson, O., Bauer, M., and Froebrich, J., 2014, River flow regime and snow cover of the Pamir Alay (Central Asia) in a changing climate: *Hydrogeological Sciences Journal*, v. 59, no. 8, pp. 1491–1506.
- Conde, V., Nico, G., Mateus, P., Catalao, J., Kontu, A., and Gritsevich, M., 2019, On the estimation of temporal changes of snow water equivalent by spaceborne SAR interferometry: a new application for the Sentinel-1 mission: *Journal of Hydrology and Hydromechanics*, v. 67, no. 1, p. 93–100.
- Cretaux, J.-F., Letolle, R., and Bergé-Nguyen, M., 2013, History of Aral Sea level variability and current scientific debates: *Global and Planetary Change*, v. 110, pp. 99–113.
- Delaloye, R., Lambiel, C., and Gärtner-Roer, I., 2010, Overview of rock glacier kinematics research in the Swiss Alps: *Swiss Journal of Geography*, v. 65, no. 2, pp. 135–145.
- Denzinger, F., 2018, Structure from motion using historical aerial images to analyse changes in surface elevation and volume on Abramov Glacier, Kyrgyzstan [MSc thesis]. University of Zurich, Switzerland.
- Dietz, A. J., Conrad, C., Kuenzer, C., Gesell, G., and Dech, S., 2014, Identifying changing snow cover characteristics in Central Asia between 1986 and 2014 from remote sensing data: *Remote Sensing*, v. 6, pp. 12752–12775.
- Duethmann, D., Bolch, T., Farinotti, D., Kriegel, D., Vorogushyn, S., Merz, B., Pieczonka, T., Jiang, T., Su, B., and Güntner, A., 2015, Attribution of streamflow trends in snow and glacier melt-dominated catchments of the Tarim River, Central Asia: *Water Resources Research*, v. 51, pp. 4727–4750.
- Dyrgerov, M. B., 2002, *Glacier Mass Balance and Regime: Data of Measurements and Analysis*. Occasional Paper No. 55. Institute of Arctic and Alpine Research, University of Colorado, Boulder, Colorado, USA
- Dyrgerov, M. B. and Dwyer, J. D., 2001, The steepening of glacier mass balance gradients with northern hemisphere warming: *Zeitschrift für Gletscherkunde und Glazialgeologie*, v. 36, pp. 107–118.
- Dyrgerov, M. B., Mikhalev, V. N., Kunakhovitch, M. G., Ushnurtsev, S. N., Liu, C., and Xie, Z., 1994, On the cause of glacier mass balance variations in the Tien Shan Mountains: *GeoJournal*, v. 33, no. 2–3, pp. 311–317.
- Erokhin, S. A., Zaginaev, V. V., Meleshko, A. A., Ruiz-Villanueva, V., Petrakov, D., Chernomoret, S. S., Viskhadzhieva, S. K., Tutubalina, O., and Stoffel, M., 2018, Debris flows triggered from non-stationary glacier lake outbursts: the case of the Teztor Lake complex (Northern Tian Shan, Kyrgyzstan): *Landslides*, v. 15, no. 1, pp. 83–98.
- Farinotti, D., Longuevergne, L., Moholt, G., Duethmann, D., Mölg, T., Bolch, T., Vorogushyn, S., and Güntner, A., 2015, Substantial glacier mass loss in the Tien Shan over the past 50 years: *Nature Geoscience*, v. 8, pp. 716–722.
- Finaev, A., 2009, Review of hydrometeorological observations in Tajikistan for the period of 1990–2005. In Braun, L. N., Hagg, W., Severskiy, I. V., and Young, G. (eds), *Proceedings Assessment of Snow, Glacier and Water Resources in Asia, Almaty, Kazakhstan, 2006, Volume 8*. UNESCO-IHP and German IHP/HWRP National Committee, Koblenz, Germany, pp. 55–64.

- Forsythe, N., Fowler, H. J., Li, X.-F., Blenkinsop, S., and Pritchard, D., 2017, Karakoram temperature and glacial melt driven by regional atmospheric circulation variability: *Nature Climate Change*, v. 7, pp. 664–670.
- Gafurov, A. and Bârdossy, A., 2009, Cloud removal methodology from MODIS snow cover product: *Hydrology and Earth System Sciences*, v. 13, no. 7, pp. 1361–1373.
- Gafurov, A., Kriegel, D., Vorogushyn, S., and Merz, B., 2013, Evaluation of remotely sensed snow cover product in Central Asia: *Hydrology Research*, v. 44, no. 3, pp. 506–522.
- Gafurov, A., Ludtke, S., Unger-Shayesteh, K., Vorogushyn, S., Schöne, T., Schmidt, S., Kalashnikova, O., and Merz, B., 2016, MODSNOW-Tool: an operational tool for daily snow cover monitoring using MODIS data: *Environmental Earth Science*, v. 75, no. 1078, pp. 1–15.
- Gardelle, J., Berthier, E., Arnaud, Y., and Kääb, A., 2013, Region-wide glacier mass balance over the Pamir-Karakoram-Himalaya during 1999–2011: *The Cryosphere*, v. 7, pp. 1263–1286.
- Gardner, A. S., Moholdt, G., Cogley, J. G., Wouters, B., Arendt, A. A., Wahr, J., Berthier, E., Hock, R., Pfeffer, W. T., Kaser, G., Ligtenberg, S. R. M., Bolch, T., Sharp, M. J., Hagen, J. O., van den Broeke, M. R., and Paul, F., 2013, A reconciled estimate of glacier contributions to sea level rise: 2003 to 2009: *Science*, v. 340, pp. 852–857.
- Glazirin, G. E., 2009, Hydrometeorological monitoring system in Uzbekistan. In Braun, L. N., Hagg, W., Severskiy, I. V., and Young, G. (eds), *Proceedings Assessment of Snow, Glacier and Water Resources in Asia, Almaty, Kazakhstan, 2006, Volume 8*. UNESCO-IHP and German IHP/HWRP National Committee, Koblenz, Germany, pp. 65–83.
- Glazirin, G. E., Braun, L., and Shchetinnikov, A. S., 2002, Sensitivity of mountain glacierization to climatic changes in Centra Asia: *Zeitschrift für Gletscherkunde und Glazialgeologie*, v. 38, no. 1, pp. 71–76.
- Goerlich, F., Bolch, T., Mukherjee, K., and Pieczonka, T., 2017, Glacier mass loss during the 1960s and 1970s in the Ak-Shirak range (Kyrgyzstan) from multiple stereoscopic corona and hexagon imagery: *Remote Sensing*, v. 9, no. 3, p. 275.
- Gorbunov, A. and Nemov, A. E., 1978, Kissledovaniu temperatur rykhlooblomochnyh tolschsh vysokogor-nogo Tyan-Shanya (On temperature research of loose deposits in the Tien Shan high mountains). *Cryogenic Phenomena of High Mountains*. Nauka, Novosibirsk, Russia, pp. 92–99 [in Russian].
- Gorbunov, A., Severskiy, E., and Titkov, S. N., 1996, Geocriologicheskie Usloviya Tyan-Shanya i Pamira (Geocryological Conditions of the Tien Shan and Pamir). Permafrost Institute, Yakutsk, Russia [in Russian].
- Gorbunov, A. P., 1978, Permafrost investigations in high-mountain regions: *Arctic and Alpine Research*, v. 10, no. 2, pp. 283–294.
- Gorbunov, A. P. and Titkov, S. N., 1992, Dynamics of rock glaciers of the northern Tien Shan and the Djungar Ala Tau, Kazakhstan: *Permafrost and Periglacial Processes*, v. 3, pp. 29–39.
- Gruber, F. E. and Margili, M., 2013, Regional-scale analysis of high-mountain multi-hazard and risk indicators in the Pamir (Tajikistan) with GRASS GIS: *Natural Hazards and Earth System Sciences*, v. 13, pp. 2779–2796.
- Gruber, S., 2012, Derivation and analysis of a high-resolution estimate of global permafrost zonation: *The Cryosphere*, v. 6, pp. 221–233.
- Gruber, S., King, L., Kohl, T., Herz, T., Haeberli, W., and Hoelzle, M., 2004, Interpretation of geothermal profiles perturbed by topography: The Alpine permafrost boreholes at Stockhorn Plateau, Switzerland: *Permafrost and Periglacial Processes*, v. 15, no. 4, pp. 349–357.
- Haeberli, W., 2008, Changing views of changing glaciers. In Orlove, B., Wiegandt, E., and Luckman, B. H. (eds), *The Darkening Peaks: Glacial Retreat in Scientific and Social Context*, University of California Press, Oakland, California, USA, pp. 23–32.
- Haeberli, W., Noetzel, J., Arenson, L., Delaloye, R., Gärtner-Roer, I., Gruber, S., Isaksen, K., Kneisel, C., Krautblatter, M., and Phillips, M., 2010, Mountain permafrost: development and challenges of a young research field: *Journal of Glaciology*, v. 56, no. 200, pp. 1040–1058.
- Hagg, W., Braun, L., Kuhn, M., and Nesgaard, T. I., 2007, Modelling of hydrological response to climate change in glacierized Central Asian catchments: *Journal of Hydrology*, v. 332, pp. 40–53.
- Hagg, W., Hoelzle, M., Wagner, S., Mayr, E., and Klose, Z., 2013, Glacier and runoff changes in the Rukhk catchment, upper Amu-Darya basin until 2050: *Global and Planetary Change*, v. 110, pp. 62–73.
- Harrison, S., Kargel, J. S., Huggel, C., Reynolds, J., Shugar, D. H., Betts, R. A., Emmer, A., Glasser, N., Haritashya, U. K., Klimes, J., Reinhardt, L., Schaub, Y., Wiltshire, A., Regmi, D., and Vilimek, V., 2018, Climate change and the global pattern of moraine-dammed glacial lake outburst floods: *The Cryosphere*, v. 12, no. 4, pp. 1195–1209.

- Hauck, C., 2013, New concepts in geophysical surveying and data interpretation for permafrost: *Permafrost and Periglacial Processes*, v. 24, no. 2, pp. 131–137.
- Hoelzle, M., Azisov, E., Barandun, M., Huss, M., Farinotti, D., Gafurov, A., Hagg, W., Kenzhebaev, R., Kronenberg, M., Machguth, H., Merkulshkin, A., Moldobekov, B., Petrov, M., Saks, T., Salzmann, N., Schöne, T., Tarasov, Y., Usualiev, R., Vorogushyn, S., Yakovlev, A., and Zemp, M., 2017, Re-establishing glacier monitoring in Kyrgyzstan and Uzbekistan, Central Asia: *Geoscientific Instrumentation Method and Data Systems*, v. 6, pp. 397–418.
- Holzer, N., Vijay, S., Yao, T., Xu, B., Buchroithner, M., and Bolch, T., 2015, Four decades of glacier variations at muztagh ata (eastern pamir): a multi-sensor study including hexagon kh-9 and pléiades data: *The Cryosphere*, v. 9, no. 6, pp. 2071–2088.
- Huss, M., Bookhagen, B., Huggel, C., Jacobsen, D., Bradley, R. S., Clague, J. J., Vuille, M., Buytaert, W., Cayan, D. R., Greenwood, G., Mark, B. G., Milner, A. M., Weingartner, R., and Winder, M., 2017, Toward mountains without permanent snow and ice: *Earth's Future*, v. 5, no. 5, pp. 418–435.
- Huss, M. and Hock, R., 2018, Global-scale hydrological response to future glacier mass loss: *Nature Climate Change*, v. 8, pp. 135–140.
- Immerzeel, W. W., Droogers, P., de Jong, S. M., and Bierkens, M. F. P., 2009, Large-scale monitoring of snow cover and runoff simulation in Himalayan river basins using remote sensing: *Remote Sensing of Environment*, v. 113, pp. 40–49.
- Janský, B., Šobr, M., Engel, S., and Yerokhin, S., 2008, High-altitude lake outburst: Tien-Shan case study. In Dostál, P. (ed.), *Evolution of Geographical Systems and Risk Processes in the Global Context*. P3K Publishers, Prague, pp. 113–127.
- Kääb, A., Leinss, S., Gilbert, A., Bühler, Y., Gascoin, S., Evans, S., Bartelt, P., Berthier, E., Brun, F., Chao, W.-A., Farinotti, D., Gimbert, F., Guo, W. Q., Huggel, C., Kargel, J. S., Leonard, G. J., Tian, L., Treichler, D., and Yao, T., 2018, Massive collapse of two glaciers in western Tibet in 2016 after surge-like instability: *Nature Geoscience*, v. 11, pp. 114–120.
- Kääb, A., Treichler, D., Nuth, C., and Berthier, E., 2015, Contending estimates of 2003–2008 glacier mass balance over the Pamir–Karakoram–Himalaya: *The Cryosphere*, v. 9, pp. 557–564.
- Kalashnikova, O. and Gafurov, A., 2017, Water availability forecasting for Naryn River using ground-based and satellite snow cover data: *Ice and Snow*, v. 57, no. 4, pp. 507–517.
- Kapitsa, V., Shahgedanova, M., Machguth, H., Severskiy, E., and Medeu, A., 2017, Assessment of evolution and risks of glacier lake outbursts in the Djungarskiy Alatau, Central Asia, using Landsat imagery and glacier bed topography modelling: *Natural Hazards and Earth System Sciences*, v. 17, pp. 1837–1856.
- Kaser, G., Grosshauser, M., and Marzeion, B., 2010, Contribution potential of glaciers to water availability in different climate regimes: *PNAS*, v. 107, no. 47, pp. 20223–20227.
- Kenzhebaev, R., Barandun, M., Kronenberg, M., Yaning, C., Usualiev, R., and Hoelzle, M., 2017, Mass balance observations and reconstruction for Batysh Sook Glacier, Tien Shan, from 2004 to 2016: *Cold Regions Science and Technology*, v. 135, pp. 76–89.
- Khan, V. and Holko, L., 2009, Snow cover characteristics in the Aral Sea Basin from different data sources and their relation with river runoff: *Journal of Marine Systems*, v. 76, no. 3, pp. 254–262.
- Khromova, T. E., Dyurgerov, M. B., and Barry, R. G., 2003, Late-twentieth century changes in glacier extent in the Ak-Shirak Range, Central Asia, determined from historical data and ASTER imagery: *Geophysical Research Letters*, v. 30, no. 16. doi:10.1029/2003GL017233.
- Khromova, T. E., Osipova, G. B., Tsvetkov, D. G., Dyurgerov, M. B., and Barry, R. G., 2006, Changes in glacier extent in the eastern Pamir, Central Asia, determined from historical data and ASTER imagery: *Remote Sensing of Environment*, v. 102, pp. 24–32.
- Knoche, M., Merz, R., Lindner, M., and Weise, S. M., 2017, Bridging glaciological and hydrological trends in the Pamir Mountains, Central Asia: *Water*, v. 9, no. 6, pp. 422.
- Komatsu, T. and Watanabe, T., 2014, Glacier-related hazards and their assessment in the Tajik Pamir: a short review: *Geographical Studies*, v. 88, no. 2, pp. 117–131.
- Koven, C. D., Ringeval, B., Friedlingstein, P., Ciais, P., Cadule, P., Khvorostyanov, D., Krinner, G., and Tarnocai, C., 2011, Permafrost carbon-climate feedbacks accelerate global warming: *PNAS*, v. 108, no. 36, pp. 14769–14774.
- Krenke, A. N., 1998, Former Soviet Union hydrological snow surveys. In N. S. a. I. D. C. a. W. D. C. f. (ed.), *Glaciology*. National Snow and Ice Data Center and World Data Center for Glaciology, Boulder, CO, USA.



- Kriegel, D., Mayer, C., Hagg, W., Vorogushyn, S., Duethmann, D., Gafurov, A., and Farinotti, D., 2013, Changes in glacierisation, climate and runoff in the second half of the 20th century in the Naryn basin, Central Asia: *Global and Planetary Change*, v. 110, pp. 51–61.
- Kronenberg, M., Barandun, M., Hoelzle, M., Huss, M., Farinotti, D., Azisov, E., Usulbajev, R., Gafurov, A., Petrakov, D., and Käab, A., 2016, Mass balance reconstruction for Glacier 354, Tien Shan, from 2003–2014: *Annals of Glaciology*, v. 57, no. 71, pp. 92–102.
- Krysanova, V., Hattermann, F., Huang, S., Hesse, C., Vetter, T., and Liersch, S., 2015, Modelling climate and land-use change impacts with SWIM: lessons learnt from multiple applications: *Hydrogeological Sciences Journal*, v. 60, no. 4, pp. 606–635.
- Kundzewicz, Z. W., Merz, B., Vorogushyn, S., Hartmann, G., Duethmann, D., Wortmann, M., Huang, S., Su, B., and Jiang, T., 2015, Analysis of changes in climate and river discharge with focus on seasonal runoff predictability in the Aksu River Basin: *Environmental Earth Sciences*, v. 73, no. 2, pp. 501–516.
- Kure, S., Jang, S., Ohara, N., Kavvas, M. L., Chen, Z. Q., 2013, Hydrologic impact of regional climate change for the snowfed and glacierfed river basins in the Republic of Tajikistan: hydrological response of flow to climate change: *Hydrological Processes*, v. 27, no. 26, pp. 4057–4070.
- Kutuzov, S. and Shahgedanova, M., 2009, Changes in the extent of glaciers in the Eastern Terskey Alatau, the Central Tien-Shan, in response to climatic fluctuations in between the end of 19th and the beginning of the 21st century: *Global and Planetary Change*, v. 69, pp. 59–70.
- Kuzmichenok, V., 2009, Monitoring of water, snow and glacial resources of Kyrgyzstan. In Braun, L. N., Hagg, W., Severskiy, I. V., and Young, G. (eds), *Proceedings Assessment of Snow, Glacier and Water Resources in Asia, Almaty, Kazakhstan, 2006, Volume 8*. UNESCO-IHP and German IHP/HWRP National Committee, Koblenz, Germany, pp. 84–98.
- Li, J., Li, Z., Zhu, J., Li, X., Xu, B., Wang, Q., Huang, C., and Hu, J., 2017, Early 21st century glacier thickness changes in the Central Tien Shan: *Remote Sensing of Environment*, v. 192, pp. 12–29.
- Li, Z. Q., Li, H. L., and Chen, Y. N., 2011, Mechanisms and simulation of accelerated shrinkage of continental glaciers: a case study of Urumqi Glacier No. 1 in Eastern Tianshan, Central Asia: *Journal of Earth Science*, v. 22, no. 4, pp. 423–430.
- Lin, H., Li, G., Cuo, L., Hooper, A., and Ye, Q., 2017, A decreasing glacier mass balance gradient from the edge of the upper Tarim basin to the Karakoram during 2000–2014: *Scientific Reports*, v. 7, no. 1, p. 6712.
- Liu, Q. and Liu, S., 2016, Response of glacier mass balance to climate change in the Tianshan mountains during the second half of the twentieth century: *Climate Dynamics*, v. 46, no. 1–2, pp. 303–303§306.
- Magnin, F., Deline, P., Ravanel, L., Noetzli, J., and Pogliotti, P., 2015, Thermal characteristics of permafrost in the steep alpine rock walls of the Aiguille du Midi (Mont Blanc Massif, 3842m a.s.l): *The Cryosphere*, v. 9, pp. 109–121.
- Magnin, F., Josnin, J.-Y., Ravanel, L., Pergaud, J., Pohl, B., and Deline, P., 2017, Modelling rock wall permafrost degradation in the Mont Blanc massif from the LIA to the end of the 21st century: *The Cryosphere*, v. 11, pp. 1813–1834.
- Marchenko, S., Gorbunov, A., and Romanovsky, V. E., 2007, Permafrost warming in the Tien Shan Mountains, Central Asia: *Global and Planetary Change*, v. 56, pp. 311–327.
- Marty, C., 2008, Regime shift of snow days in Switzerland: *Geophysical Research Letters*, v. 35, p. L12501.
- Mateo, E. I. and Daniels, J. M., 2018, Surface hydrological processes of rock glaciated basins in the San Juan Mountains, Colorado: *Physical Geography*, p. 1–19.
- Mergili, M., Kopf, C., Müllebnner, B., and Schneider, J. F., 2012, Changes of the cryosphere and related geohazards in the high-mountain areas of Tajikistan and Austria: a comparison: *Geografiska Annaler Series a-Physical Geography*, v. 93, pp. 79–96.
- Mergili, M., Müller, J. P., and Schneider, J. F., 2013, Spatio-temporal development of high-mountain lakes in the headwaters of the Amu Darya River (Central Asia): *Global and Planetary Change*, v. 107, pp. 13–24.
- Merkushkin, A. and Tsarev, B., 2007, Regime of snow accumulation and snow melting in river basin Sangardak: *Proceedings of NGIMI*, v. 8, no. 253, pp. 63–70.
- Micklin, P., 2007, The Aral Sea disaster: *Annual Review of Earth and Planetary Sciences*, v. 35, pp. 47–72.
- Mölg, N., Bolch, T., Rastner, P., Strozzi, T., and Paul, F., 2018, A consistent glacier inventory for Karakoram and Pamir derived from Landsat data: distribution of debris cover and mapping challenges: *Earth System Science Data*, v. 10, pp. 1807–1827.



- Müllebnner, B., 2010, Modelling of potential permafrost areas in the Pamir and Alai Mountains (Tajikistan) using remote sensing and GIS techniques. M.Sc. thesis, BOKU University, Vienna, Austria. Retrieved 12 May 2019, [https://abstracts.boku.ac.at/oe\\_list.php?paID=3&paSID=7913&paSF=-1&paCF=0&paLIST=0&language\\_id=DE](https://abstracts.boku.ac.at/oe_list.php?paID=3&paSID=7913&paSF=-1&paCF=0&paLIST=0&language_id=DE).
- Narama, C., Käab, A., Duishonakunov, M., and Abdrakhmatov, K., 2010, Spatial variability of recent glacier changes in the Tien Shan Mountains, Central Asia Corona (~1970), Landsat (~2000), and ALOS (~2007) satellite data: *Global and Planetary Change*, v. 71, pp. 42–54.
- Noetzli, J. and Gruber, S., 2009, Transient thermal effects in Alpine permafrost: *The Cryosphere*, v. 3, pp. 85–99.
- Noetzli, J., Gruber, S., Kohl, T., Salzmann, N., and Haeberli, W., 2007, Three-dimensional distribution and evolution of permafrost temperatures in idealized high-mountain topography: *Journal of Geophysical Research*, v. 112, no. F02S13. doi:10.1029/2006JF000545.
- Ozmonov, A., Bolch, T., Xi, C., Wei, J., Kurban, A., and Guo, W. Q., 2013, Glacier characteristics and changes in the Sary-Jaz river basin (Central Tien Shan) 1990–2010: *Remote Sensing Letters*, v. 4, no. 8, pp. 725–734.
- Paul, F. and Mölg, N., 2014, Hasty retreat of glaciers in northern Patagonia from 1985 to 2011: *Journal of Glaciology*, 60, pp. 1033–1043.
- Peters, J., Bolch, T., Gafurov, A., and Prechtel, N. 2015, Snow cover distribution in the Aksu catchment (Central Tien Shan) 1986–2013 based on AVHRR and MODIS data: *IEEE Journal of Selected Topics of Applied Earth Observation*, v. 8, no. 11, pp. 5361–5375.
- Petrov, M. A., Sabitov, T. Y., Tomashevskaya, I. G., Glazirin, G. E., Chernomorets, S. S., Savernyuk, E. A., Tutubalina, O. V., Petrakov, D. A., Sokolov, L. S., Dokukin, M. D., Mountrakis, G., Ruiz-Villanueva, V., and Stoffel, M., 2017, Glacial lake inventory and lake outburst potential in Uzbekistan: *Science of the Total Environment*, v. 592, pp. 228–242.
- Pieczonka, T., Bolch, T., Wei, J., and Liu, S. (2013) Heterogeneous mass loss of glaciers in the Aksu-Tarim Catchment (Central Tien Shan) revealed by 1976 KH-9 Hexagon and 2009 SPOT-5 stereo imagery: *Remote Sensing of the Environment*, 130, pp. 233–244.
- Pieczonka, T. and Bolch, T., 2015, Region-wide glacier mass budgets and area changes for the Central Tien Shan between ~1975 and 1999 using Hexagon KH-9 imagery: *Global and Planetary Change*, v. 128, pp. 1–13.
- Pohl, E., Gloaguen, R., Andermann, C., and Knoche, M., 2017, Glacier melt buffers river runoff in the Pamir Mountains: *Water Resources Research*, v. 53, pp. 2467–2489.
- Prein, A. F., Langhans, W., Fossier, G., Ferrone, A., Ban, N., Goergen, K., Keller, M., Tölle, M., Gutjahr, O., Feser, F., Brisson, E., Kollet, S., Schmidli, J., van Lipzig, N. P. M., and Leung, R., 2015, A review on regional convection-permitting climate modeling: Demonstrations, prospects, and challenges: *Reviews of Geophysics*, v. 53, no. 2, pp. 323–361.
- RGI Consortium, R., 2017, Randolph Glacier Inventory (RGI) – A Dataset of Global Glacier Outlines. In G. L. I. M. f. (ed.), *Space. Global Land Ice Measurements from Space*, Boulder, CO, USA.
- Sakai, A., Nuimura, T., Fujita, K., Takenaka, S., Nagai, H., and Lamsal, D., 2015, Climate regime of Asian glaciers revealed by GAMDAM glacier inventory: *The Cryosphere*, v. 9, no. 3, pp. 865–880.
- Schwarzman, U. G., 1985, Geotermicheskii rejim, dinamika litosfery I perspektivy ispolzovaniya geotermicheskoi energii Tien-Shanya (in Russian) (Geothermic regime, dynamics of lithosphere, and perspectives of using geothermal energy of the Tien Shan). *Geothermic Investigations in Middle Asia and Kazakhstan*. Nauka, Moscow, pp. 236–250.
- Seneviratne, S. I., Donat, M. G., Pitman, A. J., Knutti, R., and Wilby, R. L., 2016, Allowable CO2 emissions based on regional and impact-related climate targets: *Nature*, v. 529, no. 7587, pp. 477–483.
- Serquet, G., Marty, C., and Rebetez, M., 2013, Monthly trends and the corresponding altitudinal shift in the snowfall/precipitation day ratio: *Theoretical and Applied Climatology*, v. 114, pp. 437–444.
- Shahgedanova, M., Afzal, M., Severskiy, E., Usmanova, Z., Saidaliyeva, Z., Kapitsa, V., Kasatkin, N., and Dolgikh, S., 2018, Changes in the mountain river discharge in the northern Tien Shan since the mid-20th Century: Results from the analysis of a homogeneous daily streamflow data set from seven catchments: *Journal of Hydrology*, v. 564, pp. 1133–1152.
- Shangguan, D., Liu, S., Ding, Y., Ding, L., Xiong, L., Cai, D., Li, G., Lu, A., Zhang, S., and Zhang, Y., 2006, Monitoring the glacier changes in the Muztag Ata and Konggur mountains, East Pamirs, based on Chinese glacier inventory and recent satellite imagery: *Annals of Glaciology*, v. 43, pp. 79–85.
- Sorg, A., Bolch, T., Stoffel, M., Solomina, O., and Beniston, M., 2012, Climate change impacts on glaciers and runoff in Central Asia: *Nature Climate Change*. doi: 10.1038/nclimate1592.

- Sorg, A., Huss, M., Stoffel, M., and Rohrer, M., 2014, The days of plenty might soon be over in glacierized Central Asian catchments: *Environmental Research Letters*, v. 9, p. 104018.
- Sorg, A., Kääb, A., Roesch, A., Bigler, C., and Stoffel, M., 2015, Contrasting responses of Central Asian rock glaciers to global warming: *Scientific Reports*, v. 5, p. 8228.
- Stoffel, M. and Huggel, C., 2012, Effects of climate change on mass movements in mountain environments: *Progress in Physical Geography*, v. 36, pp. 421–439.
- Tsarev, B., 2006, Assessment of climate change impact on maximum snow storage in Central Asian mountains: *Proceedings of NGIMI*, v. 4, no. 249, pp. 15–32.
- Tweed, F. S. and Carrivick, J. L., 2015, Deglaciation and proglacial lakes: *Geology Today*, v. 31, no. 3, pp. 96–102.
- Unger-Shayesteh, K., Vorogushyn, S., Farinott, D., Gafurov, A., Duethmann, D., Mandychev, A., and Merz, B., 2013, What do we know about past changes in the water cycle of Central Asian headwaters? A review: *Global and Planetary Change*, v. 110, pp. 4–25.
- Wang, Q., Yi, S., Chang, L., and Sun, W., 2017, Large-scale seasonal changes in glacier thickness across high mountain asia: *Geophysical Research Letters*, v. 44, pp. 10427–10435.
- Wang, S. and Zhang, T., 2013, Glacial lakes change and current status in the central Chinese Himalayas from 1990 to 2010: *Journal of Applied Remote Sensing*, v. 7, pp. 1–15.
- WGMS, 2017, Global Glacier Change Bulletin No. 2 (2014–2015). In Zemp, M., Nussbaumer, S. U., Gärtner-Roer, I., Huber, J., Machguth, H., Paul, F., and Hoelzle, M. (eds), *Global Glacier Change Bulletin, Volume 2*. ICSU(WDS)/IUGG(IACS)/ UNEP/UNESCO/WMO, World Glacier Monitoring Service, Zurich, Switzerland, p. 244.
- Würzer, S., Jonas, T., Wever, N., and Lehning, M., 2016, Influence of initial snowpack properties on runoff formation during rain-on-snow events: *Journal of Hydrometeorology*, v. 17, no. 6, pp. 1801–1815.
- Xenarios, S., Gafurov, A., Schmidt-Vogt, D., Sehring, J., Manandhar, S., Hergarten, C., Shigaeva, J., and Foggin, M., 2019, Climate change and adaptation of mountain societies in Central Asia: uncertainties, knowledge gaps, and data constraints: *Regional Environmental Change*, v. 19, pp. 1339.
- Yakovlev, A., 2005, Method of the Pyandzh river runoff simulation during flood season with use of numerical weather predicted data and satellite images: *Proceedings of NGIMI*, v. 5, no. 250, pp. 123–134.
- Zemp, M., Haeberli, W., Hoelzle, M., and Paul, F., 2006, Alpine glaciers to disappear within decades?: *Geophysical Research Letters*. doi:10.1029/2006GL026319.
- Zhou, H., Aizen, E. M., and Aizen, V. B., 2013, Deriving long term snow cover extent dataset from AVHRR and MODIS data: Central Asia case study: *Remote Sensing of the Environment*, v. 136, pp. 146–162.